Fission Surface Power Technology Demonstration Unit Test Results

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The Fission Surface Power (FSP) Technology Demonstration Unit (TDU) is a system-level demonstration of fission power technology intended for use on manned missions to Mars. The Baseline FSP systems consists of a 190 kWt UO2 fast-spectrum reactor cooled by a primary pumped liquid metal loop. This liquid metal loop transfers heat to two intermediate liquid metal loops designed to isolate fission products in the primary loop from the balance of plant. The intermediate liquid metal loops transfer heat to four Stirling Power Conversion Units (PCU), each of which produce 12 kWe (48 kW total) and reject waste heat to two pumped water loops, which transfer the waste heat to titanium-water heat pipe radiators. The FSP TDU simulates a single leg of the baseline FSP system using an electrically heater core simulator, a single liquid metal loop, a single PCU, and a pumped water loop which rejects the waste heat to a Facility Cooling System (FCS). When operated at the nominal operating conditions (modified for low liquid metal flow) during TDU testing the PCU produced 8.9 kW of power at an efficiency of 21.7% resulting in a net system power of 8.1 kW and a system level efficiency of 17.2%. The reduction in PCU power from levels seen during electrically heated testing is the result of insufficient heat transfer from the NaK heater head to the Stirling acceptor, which could not be tested at Sunpower prior to delivery to GRC. The maximum PCU power of 10.4 kW was achieved at the maximum liquid metal temperature of 875 K, minimum water temperature of 350 K, 1.1 kg/s liquid metal flow, 0.39 kg/s water flow, and 15.0 mm amplitude at an efficiency of 23.3%. This resulted in a system net power of 9.7 kW and a system efficiency of 18.7 %.

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I. Introduction

THE Fission Surface Power System (FSPS) is intended for use on manned missions to Mars which have relatively high power requirements. The Baseline FSPS consists of a 190 kWt UO2 fast-spectrum reactor cooled by a primary pumped liquid metal loop. This liquid metal loop transfers heat to two intermediate liquid metal loops designed to isolate fission products in the primary loop from the balance of plant. The intermediate liquid metal loops transfer heat to four Stirling Power Conversion Units (PCU), each of which produce 12 kWe (48 kW total) and reject waste heat to two pumped water loops, which transfer the waste heat to titanium-water heat pipe radiators (Ref 1). This FSPS design was the result of the Affordable Fission Power Study (Ref 2) commissioned by NASA HQ and was considered the baseline power system for DRA 5.0 (Ref 3).

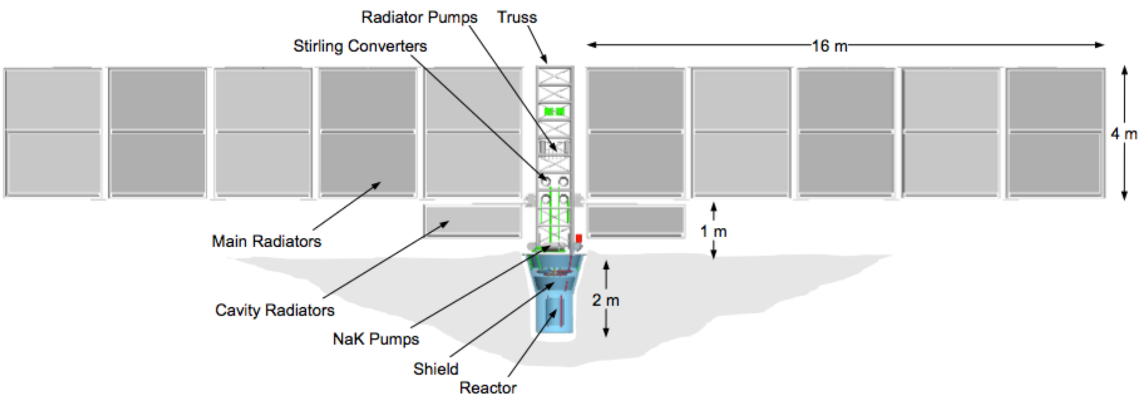

Figure 1. Schematic of the 40 kW$_e$ Fission Surface Power System

The original design of the FSP TDU simulated a single leg of the baseline FSP system using an electrically heater core simulator, primary and secondary liquid metal loops, a single Stirling PCU, and a pumped water loop which rejected heat to 6 titanium-water heat pipe radiators. TDU testing was intended to demonstration the Balance of Plant (BoP) of the FSP to TRL 6 (Ref 4). After several reductions in budget and organizational changes, the TDU scope was reduced, resulting in removal of the secondary liquid metal loop, radiators, and power conditioning. In addition, testing was focused on system performance, removing several transient response scenarios from the original test matrix. Figure 2 shows schematics of the TDU as originally designed and as tested.

Several component and sub-system level tests were conducted prior to system-level TDU testing (Ref 5-16). These included component testing of two Annular Linear Induction Pumps (ALIP) and the Core Simulator at MSFC, sub-scale Stirling testing at GRC and MSFC, testing of full-scale Stirling PCU at Sunpower Inc, radiator panel testing, and sub-system testing of both the liquid metal and water loops at GRC. ALIP testing at MSFC revealed that the Annular Linear Induction Pump (ALIP) used to pump the liquid metal achieved 5% efficiency compared to an expected value of 10% at the nominal operating condition of 850 K, 1.75 kg/s, and 28 kPa liquid metal loop pressure drop. The reduced ALIP efficiency increases the power required to achieve a given flow rate, increasing the parasitic power loss, and decreasing system efficiency. A preliminary investigation revealed

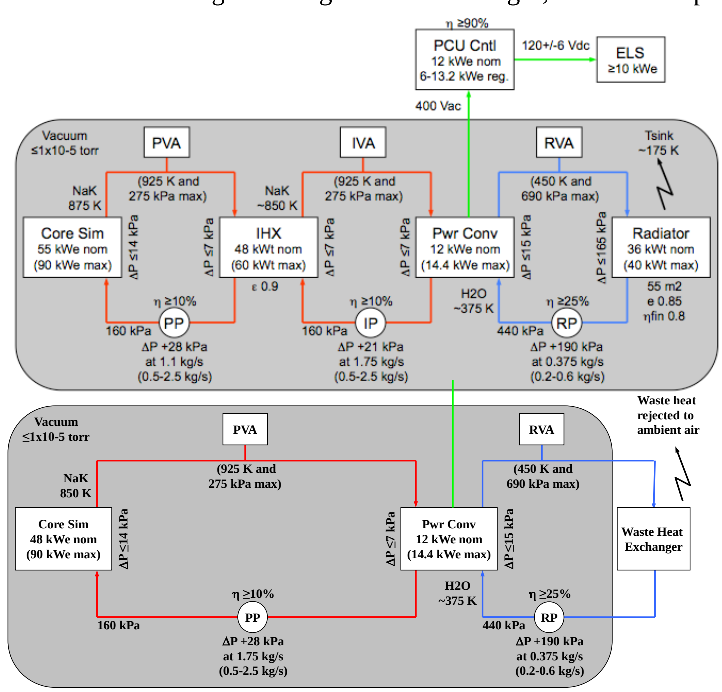

Figure 2. Schematic of the Fission Surface Power Technology Demonstration Unit showing the original configuration (upper) and the as-built configuration (lower)

several design and process improvements that could be used in future pump designs to increase pump performance closer to expected values. However, redesign and fabrication of a new pump was outside of the scope of the project, so the existing ALIP was used as-built for TDU testing. Liquid-metal sub-system checkout testing prior to system-level testing revealed an issue with one of the two ALIP power supplies. Replacement of the power supply was straight forward, but the TDU test schedule did not allow for the substantial lead time so liquid metal mass flow was limited to 1.2 kg/s throughout testing. Component testing of the PCU at Sunpower, using electric heating, showed that the PCU operating at nominal operating (850 K hot-end temperature, 375 K water temperature, 0.375 kg/s water flow rate, and 16 mm amplitude) produced 12.2 kW of power at a gross efficiency (electrical power output of the engines divided by electrical power input to the electric heaters) of 25.5%, compared to the specified values of 12.0 kW and 26% efficiency. After the conclusion of electrically heated testing, the electrically heated head was removed and replaced with a heater head that included a liquid metal heat exchanger for testing in the TDU. Since Sunpower does not have the capability to operate a pumped liquid metal loop, the TDU system-level test was the first time that the PCU was run in its final configuration.

II. TDU Test Results

After the conclusion of engine testing at Sunpower the engines were shipped to NASA GRC and integrated into the existing water and NaK subsystems. Figure 3 shows the TDU system inside of Vacuum Facility 6 at NASA GRC.

Figure 3. Photgraph of the FSP TDU installed in Vaccum Facility 6 at NASA GRC

A. Experimental Results

Figures 4 shows PCU and system level power and efficiency at nominal and maximum hot-end temperatures of 850 K and 875 K respectively, nominal and low cold-end temperatures of 375 K and 360 K respectively, and nominal and high water flow or 375 g/s and 690 g/s respectively. In addition, Figure 4 shows that maximum power point which was taken at 875 K hot-end temperature, 350 K cold-end temperature, 1.1 kg/s NaK flow, 0.39 kg/s water flow, and 15 mm amplitude. PCU power is the measured electrical output from the PCU and PCU efficiency is calculated as the electrical output divided by the enthalpy difference in the NaK measured across the PCU. System power is equal to the PCU power minus parasitic losses of the ALIP and water pump. System efficiency is the system power divided by the total heat input to the core simulator. Therefore system level efficiency takes into account all parasitic losses including insulation losses between components. It should be noted that parasitic losses in this simplified TDU system are lower than what would be expected for the original TDU configuration that included a secondary NaK loop, larger water-side pressure drop through radiators, and additional Power Management and Distribution (PMAD).

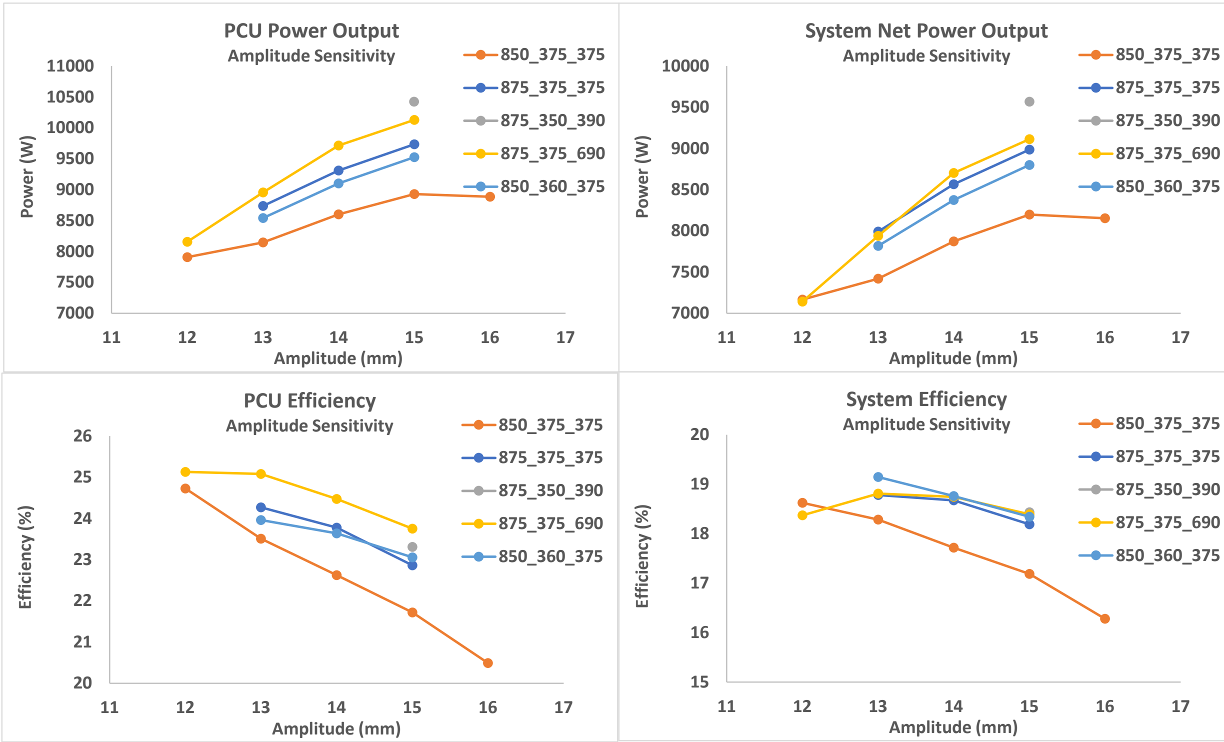

Figure 4. PCU power (upper left), System Power (upper right), PCU Efficiency (lower left), System Efficiency (lower right) for the FSP TDU.

PCU power output increases with amplitude from 12 mm to 15 mm. Between 15 mm and 16 mm the power began to decrease at the nominal operating conditions (850 K hot-end temp, 375 K cold-end temp, 1.0 kg/s NaK flow, and 0.375 kg/s water flow). Other tests at off-nominal conditions resulted in excessive piston drift between 15 mm and 16 mm which caused the piston limit sensor to stall the engines. Excessive drift was not seen during testing of the PCU at Sunpower using electric heads, suggesting piston seal clearances changed when the electric head was replaced with the NaK head for TDU testing. To avoid engine stall, testing was limited to 15 mm after an initial 16 mm point was run at nominal conditions. It is not known if the downward trend continues at higher amplitude or if the decrease in power would also have occurred during high hot-end temperature or low cold-end temperature testing. However, the PCU power output measured during NaK testing was universally lower than PCU power output measured during electrical testing at Sunpower, suggesting that there may not have been adequate thermal contact between the NaK heat exchanger and the internal acceptor. Inadequate heat transfer could contribute to the premature power plateau shown at nominal operating conditions (Orange plot in figure 4), however this conclusion has not been verified. Testing below 375 K on the cold-end resulted in excessive helium leakage of the PCU into the vacuum chamber, therefore after the initial low cold-end temperature test was run at 360 K, and maximum power point was recorded at 350 K, future tests were limited to a minimum cold-end temperature of 375K. System level power plots show that although the PCU performs better at higher water flow rates, but these gains are nearly eliminated on the system level due to increased pump power. The effect of increasing the hot-end 25 K is shown to be similar to the effect of decreasing the cold-end temperature by 15 K in both PCU and system level performance.

When operated at the nominal operating conditions the PCU produced 8.9 kW of power at an efficiency of 21.7% resulting in a net system power of 8.1 kW and a system level efficiency of 17.2%. The maximum PCU power of 10.4 kW was achieved at the maximum liquid metal temperature of 875 K, minimum water temperature of 350 K, 1.1 kg/s liquid metal flow, 0.39 kg/s water flow, and 15.0 mm amplitude at an efficiency of 23.3%. This resulted in a system net power of 9.6 kW and a system efficiency of 18.7%. The system level power and efficiency compare favorably to original system level performance specifications of 10 kW power output at 18% system efficiency (Ref 4).

B. Numerical Model Results

Preliminary estimates of FSP system performance and mass were made using several assumptions regarding component performance. ALIP efficiency was assumed to be 10%, Stirling PCU efficiency was assumed to reach 50% of the Carnot efficiency, and water pump efficiency was assumed to reach 25 % at the nominal operating condition, with ~ 10% thermal loss due to radiation on the hot end. Preliminary TDU models used the same assumptions predicting 12.5 kW of PCU output power at 26% efficiency resulting in 10.1 kW of net power at 18.4% efficiency at the system level when operating at nominal conditions. As components and subsystems were built and tested these models were updated to include the performance of the as-built components. Upon completion of electrically heated testing of the PCU, which reached specified power and efficiency expectations, the as-built PCU model was added to the system level model. These predictions are shown in Table 1 under the "Original Prediction" heading. When running the TDU at GRC with the NaK head, it was discovered that both power output and efficiency had decreased from what was measured during electric testing. Models were updated to include an increased thermal resistance between the NaK heat exchanger and the copper acceptor, lowering power output and efficiency. These predictions are included in the Table 1 under the "Tuned Prediction" heading. The tuned prediction column is included to show that there is good agreement between measurements and predictions when accounting for increased thermal resistance of the heater head, suggesting that this is the cause of the decrease in performance. The "Original Prediction" column is included to show the expected system performance had the thermal resistance of the NaK heads been closer to what was achieved on the electric heads. The maximum power point reached system level performance of 9.6 kW at 18.4% efficiency, which is close to the predictions of the preliminary system level models. However, this is largely due in part to the fact that reductions in component performance were offset by budget driven simplifications to the TDU design, including removal of the intermediate NaK loop, radiators, and power electronics.

HET (K)	CET (K)	NaK Flow (kg/s)	Water Flow (kg/s)	Amp (mm)	PCU Power			PCU Eff			System Power (W)			System Eff		
					Measured	Original Prediction	Tuned Prediction	Measured	Original Prediction	Tuned Prediction	Measured	Original Prediction	Tuned Prediction	Measured	Original Prediction	Tuned Prediction
850	375	1	0.375	12	7908	8377	7472	24.7	25.8	24.3	7167	7755	6846	18.6	22.7	21.0
850	375	1	0.375	13	8148	9253	8047	23.5	25.8	23.7	7421	8641	7430	18.3	23.0	20.8
850	375	1	0.375	14	8601	10126	8582	22.6	25.9	23.2	7871	9524	7974	17.7	23.4	20.6
850	375	1	0.375	15	8927	10902	9004	21.7	25.6	22.4	8196	10312	8407	17.2	23.3	20.1
850	375	1	0.375	16	8886	11620	9360	20.5	25.1	21.6	8154	11044	8773	16.3	23.0	19.5
850	360	1	0.375	13	8542	9552	8413	24.0	27.1	25.2	7818	8939	7795	19.1	24.1	22.2
850	360	1	0.375	14	9100	10451	9016	23.6	27.1	24.8	8375	9848	8406	18.8	24.4	22.0
850	360	1	0.375	15	9526	11302	9510	23.1	26.9	24.1	8800	10711	8910	18.3	24.5	21.6
875	375	1	0.69	12	8155	9244	8269	25.1	27.7	25.6	7142	8302	7324	18.4	23.4	21.3
875	375	1	0.69	13	8953	10283	9030	25.1	27.7	25.5	7940	9348	8091	18.8	23.9	21.6
875	375	1	0.69	14	9715	11299	9674	24.5	27.8	25.0	8701	10372	8743	18.7	24.3	21.5
875	375	1	0.69	15	10128	12260	10247	23.8	27.5	24.3	9113	11342	9324	18.4	24.4	21.2
875	375	1	0.375	13	8737	9922	8633	24.3	27.0	24.5	7992	9256	7964	18.8	23.9	21.4
875	375	1	0.375	14	9311	10846	9216	23.8	26.9	24.0	8566	10189	8554	18.7	24.1	21.2
875	375	1	0.375	15	9733	11686	9739	22.9	26.6	23.4	8985	11038	9085	18.2	24.1	20.8
875	350	1.1	0.39	15	10421	12391	10627	23.3	29.0	26.1	9567	11654	9878	18.4	26.1	23.2

III. PCU Helium Breach

After completion nominal cold-end temperature portion of the test matrix the TDU was taken to the high cold-end temperature condition. During this transient the helium working fluid contained within the PCU breached into the water cooling loop. This event initiated an emergency shutdown sequence in which the engines were stalled, the core simulator was turned off, residual water was vented through the drain leg and nitrogen flow was initiated to provide auxiliary cooling to the PCU. No damage was done to hardware outside of the damage done by the breach itself. However, the PCU was no longer able to hold the working gas charge pressure and TDU testing could not continue. There are currently no funds available for repair of the PCU. Figure 5 shows several parameters of interest 30 seconds prior to the helium breach. The black lines on the figures below show the moment of increased leak rate and the moment of full-on failure of the helium-water seal.

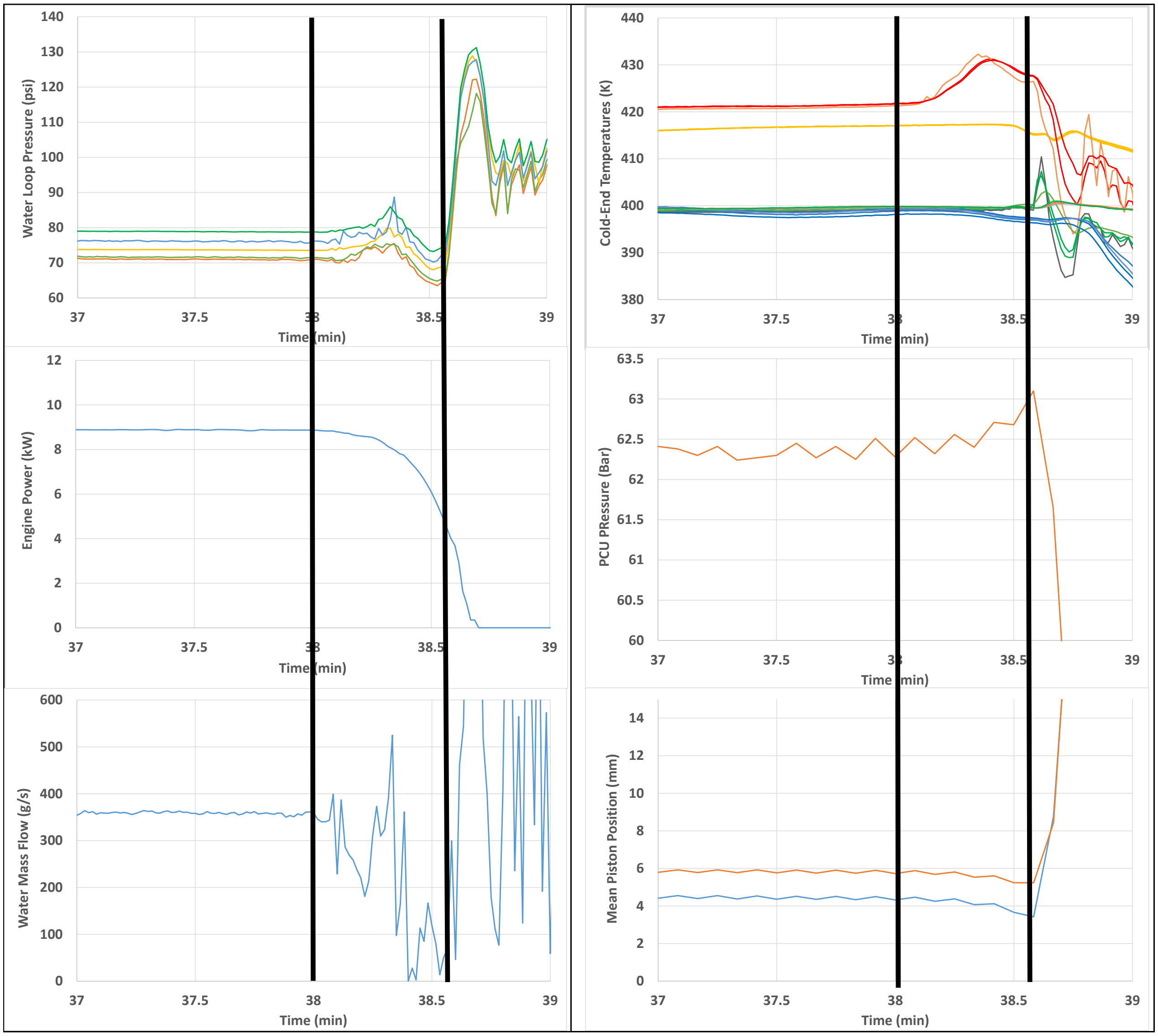

Figure 5. Water loop pressure, engine power, water mass flow, cold-end temperature, PCU helium pressure, and mean piston position in the moments preior to and during helium-water breach.

Investigation of the breach determined that a small helium leak began around 8.5 minutes prior to the rapid helium breach resulting in a gradual decrease in water mass flow rate. This leak continued, masked by increases in cold-end temperature and relief of excess water-loop pressure by a self-relieving regulator on the water accumulator for approximately 8 minutes. At that point, the helium leak rate increased, effecting other loop parameters including water loop pressure and mass flow. Thirty seconds later the helium leak rate increased dramatically, either due to natural propagation of the original failure or aided by reduced cooling to the PCU. The TDU Test Team suspects that this leak occurred in one of the elbows of the water manifold leading to the rejector, which have had documented leak and fabrication issues. Both the initial leak and the increase in leak rate occurred while the PCU was operating within specifications, suggesting redesign of PCU components and/or improvement in fabrication methods are required to avoid similar failures in the future.

IV. Conclusion

The Fission Surface Power Technology Demonstration Unit was a system level demonstration of the technologies used in the Affordable Fission Power System baselined in Design Reference Architecture 5.0. The as-built TDU was descoped from the original vision, but successfully demonstrated that a single leg of the power system proposed in the Affordable Fission Surface Power Study is capable of producing 9.6 kW of power at 18.4 % efficiency at the system

level a relevant environment which is in line with the original system level requirements of 10 kW operation at 18.4% system efficiency. The test also demonstrated steady-state performance of the system through a range of operating conditions and was used to verify and calibrate numerical performance models. Potential areas for improving system performance or the quality of test data in subsequent programs or follow-on testing include:

1. Improving ALIP design to achieve performance in line with previously built pumps.
2. Improved design of the water-helium boundary on the Stirling engine.
3. Processing the engines in a way that allows the Stirling engines with NaK heads to be tested and modified, if necessary, prior to installation in the test loop.
4. Including heat pipe radiators for accurate system response and transient feedback.
5. Improving reactivity feedback software to allow for accurate transient reactor simulations.
6. Adding power conditioning and prototypic engine control electronics to more accurately reflect mission demands.

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